Effects of combined wrist deviation and forearm rotation on discomfort score

ABID ALI KHAN†

Tel: +91 571 2700920 ext 1861

Fax: +91 571 2721375

Email: abida.khan@amu.ac.in

†Ergonomics Laboratory, Department of Mechanical Engineering, Aligarh Muslim University, Aligarh, UP, India

LEONARD O'SULLIVAN‡*

Tel: +353 61 234249

Fax: +353 61 202913

Email: leonard.osullivan@ul.ie

TIMOTHY J. GALLWEY‡

Tel and Fax: Same as Leonard O'Sullivan

Email: gallweyt@wanadoo.fr

‡Ergonomics Research Centre, Department of Manufacturing & Operations Engineering, University of Limerick, Limerick, Republic of Ireland

Abstract

The aim of the present study was to examine the pattern of the change in discomfort for combined wrist deviation and forearm rotation. There were five levels of wrist deviation (neutral, 35% and 55% of the Range Of Motion (ROM) in radial and ulnar), and five levels of forearm rotation (neutral, 30% and 60% of the ROM in prone and supine). Twenty-five participants performed a repetitive flexion task with a force of 10N$\pm$1N at a frequency of 15 exertions per minute. Repeated measures ANCOVA was used on transformed values of the discomfort scores. Wrist deviation (p=0.007), and forearm rotation (p=0.001) were significant. Interactions of the main factors were not significant, nor was the covariate. Quadratic regression equations were derived and were used to generate iso-discomfort contours which show a useful area of low discomfort around the central zone but with steep increases at the extreme combinations.

Relevance to Industry

Discomfort equations and contours are useful for the design of industrial tools, machine controls and workspaces. They can be used to reduce the risk of injury associated with the tasks or tools by avoiding bad postural deviations of the wrist and forearm.

Keywords: Wrist radial/ulnar deviation, Forearm prone/supine rotation, Raw Discomfort Score, Transformed Discomfort Score, Endurance time, and Wrist flexion MVC.

1. Introduction

There is strong evidence for the relatedness of work design factors with Work-related MusculoSkeletal Disorders (WMSDs) (Bernard, 1997). Bernard reported a positive relationship between exposure to specific task factors (such as posture, force, repetition, and combinations of these) and WMSDs, based on a comprehensive survey of studies in which chance, bias, and confounding factors could be ruled out with reasonable confidence. The literature shows that the risk of WMSDs associated with certain jobs are higher when compared with other population groups not exposed to such risk factors (Aaras et al., 1988, Hagberg, et al., 1995). Further, the US Bureau of Labour Statistics (BLS, 1995) recorded approximately 705,800 injuries from over-exertion or repetitive motions in one year. Of these, 92,576 were the result of repetitive motion, including those from typing or key entry, repetitive use of tools, and repetitive placing, grasping, or moving of objects other than tools. Of these repetitive motion injuries, 55% affected the wrist.

Blader et al. (1991) reported a high prevalence of musculoskeletal pain among sewing machine operators. Ranney et al. (1995) found that 54% of workers in highly repetitive jobs had a high incidence of upper limb musculoskeletal disorders that were potentially work related. Hashemi et al. (1998), looking at worker compensation claims from the privately insured US workers' compensation market, found that upper extremity disorder cases accounted for 6.4% of all claims costs, totalling over $130 million. The majority of WMSDs are known to develop gradually over time during occupational tasks (Putz-Anderson, 1988), and there is evidence that these problems are related to the factors of repetitiveness, force, and posture (Dimberg 1987, Hagberg, et. al. 1995, Bernard 1997). However the relative contributions of these factors to the occurrence of injuries, and their relationship to it, are not known.

Among the general workforce, upper extremity WMSDs for workers in the garment industry showed 47% prevalence of the pain symptom in the neck, 66% in the shoulder, 29% in the elbow and forearm, 24% in the wrist and 42% in the hand (Herbert et al., 2001), i.e. 66% prevalence in the hand/wrist region. Supermarket checkouts had a wrist musculoskeletal injury rate two to three times higher than that of other departments (Estill and Kroemer, 1998). Further, Silverstein (1998) reported an association between upper extremity disorders and tasks that require forceful repetitive exertions e.g. wallboard installation, roofing, foundries, construction, woodwork, paper products manufacturing, and meat dealers. Almost all these occupations involved repetitive, forceful work that required pronation/supination combined with wrist deviation.

According to Snook et al. (1997) ulnar deviation is a motion commonly found in the workers of the meat packing industry, engaged in cutting and trimming meat products. Terrell and Purswell (1976), found a 15% reduction in grip strength for 20^0 ulnar deviation and an 18% reduction for 20^0 radial deviation. Drury et al. (1985) found that wrist deviation, either ulnar or radial, causes discomfort, especially when associated with repeated force exertion at large angles (20^0). They found that radial deviation gave greater discomfort than ulnar. However, the joint postures considered in the above stated studies were in absolute values of angles (in degrees), rather than relative to the individual capability of the participants, for forearm rotation and wrist flexion. Snook et al. (1997) reported that the maximum acceptable force was least for ulnar deviation compared to flexion and extension, which may account for part of Drury et al.'s finding. However there is a lack of information on the increase in severity of the problems with increases in wrist deviation, and many tasks also involve forearm rotation. Lin et al. (1997) looked at changes in discomfort for two levels of pace and two force levels, but only for wrist flexion angles of 15^0 and 45^0. They found pace, force and wrist flexion significantly affected discomfort ($p<0.05$). They also developed regression equations to predict discomfort, but the independent variables (force and wrist flexion) were absolute values rather than relative to the individuals' maximum Ranges of Motion (ROMs). As the individuals' wrist deviation/forearm rotation ROMs may differ from one another, the relative feeling of discomfort may well be different for the same absolute angular deviation. Yet it might be similar at the same relative angular deviation with respect to the individual's ROM. Therefore it is desirable to develop a relationship for discomfort prediction with respect to the percentage ROM of the wrist and forearm of the person.

Armstrong and Chaffin (1978) reported the values for the average radius of curvature of both the profundus and superficial flexor tendons. The larger wrists were found to have larger radii of curvature so any force in the tendons would be applied over a larger surface area. Biomechanically, this could partially explain why people with small wrists are thought by some to be at higher risk of wrist injury on jobs requiring frequent and forceful manual exertions with the wrist deviated. Klein and Fernandez (1997) investigated the effects of wrist postures in relation to individual abilities, but they investigated only wrist flexion. Carey and Gallwey (2002) studied the effects on discomfort of flexion/extension with ulnar/radial deviation, in relation to individual capabilities but they excluded forearm rotation. Carey & Gallwey (2005) studied the combined effect of wrist radial/ulnar deviation with wrist flexion/extension at 15 exertions per minute for a wrist flexion force of 10N. It was reported that when wrist extension was combined with ulnar deviation, wrist extension had a highly significant effect on discomfort ($p<0.001$). Also, they found that when wrist flexion was combined with ulnar deviation, both flexion and ulnar deviation had a significant effect on discomfort ($p<0.001$ and $p<0.025$ respectively). But in many jobs these postures are combined with forearm rotation (Genaidy & Karwowski, 1993; Snook et al., 1997; Lin et al., 1997; O'Sullivan & Gallwey, 2001; Carey & Gallwey, 2002; and Carey & Gallwey, 2005).

Because of the high prevalence of torque exertions in many industrial operations Ciriello et al. (2002) determined the maximum acceptable torque (subjective) for screw driving tasks in supination/pronation in a simulated screw-driving task. O'Sullivan and Gallwey (2001) used a simulated screw-driving task to develop regression models of subjective discomfort scores for supination/pronation torques with five forearm rotations, all relative to the abilities of the participants. But the wrist was in a neutral posture. Mukhopadhyay et al. (2003) investigated three forearm rotation angles with abduction of the upper arm and found a significant effect of forearm rotation ($p<0.001$) on reported discomfort. The levels were set relative to the individuals, but they did not include any wrist deviation.

One of the difficulties is how to obtain a suitable measurement of the effects of these postures on the risk of injuries. An early step was the psychophysical technique used by Corlett and Bishop (1976), in association with a body diagram. More recently, rating scales such as a Visual Analogue Scale (VAS) have been used to estimate perceived pain (Genaidy and Karwowski 1993, Snook et. al. 1995, Lin et al. 1997, Aaras et. al. 2002, Carey and Gallwey 2002 and Labus et al. 2003). These are usually based on a 10 cm length, scaled from 0 to 10, and have the advantage of integrating the effects of all the factors into a single measure.

A further complicating factor in such research is the difference in pain tolerance between participants, particularly when using a subjective measure such as VAS. In an attempt to reduce this effect, Carey and Gallwey (1999) used endurance time in an isometric wrist flexion exertion as a covariate. Mukhopadhyay et al. (2003) found that grip endurance time and torque endurance time at 50% MVC were significant covariates ($p<0.001$) for discomfort in a repetitive torqueing task combined with grip exertion. Khan et al. (2003) examined a repetitive wrist flexion task combined with grip exertion and again endurance time was a significant covariate ($p<0.002$). These results suggest that endurance time should be used as a covariate to reduce the subjective differences in discomfort perception.

The number of studies focused on ranking the stressfulness of joint motions is limited and those in the literature have examined either forearm rotation or wrist deviation separately, even though they occur in combinations in industry (see earlier). To understand real tasks the interaction effects of these postural features are of paramount importance to develop guidance for ergonomic interventions (Silverstein et. al, 1986). The objective of this study was to identify the relative contributions of these two movements (radial/ulnar deviation of the wrist and prone/supine rotation of the forearm) of the hand/arm system in the development of discomfort, and to develop a means of predicting the relative discomfort resulting from specific combinations of these factors while exerting a repetitive force.

2. Method

2.1. Participants

Twenty-five right-handed male college students of mean age 23 years (SD 3.32), height 177 cm (SD 8.9) and mass 74.8 kg (SD 10.5) were recruited by campus notices and email announcements. The participants were paid €30 for their participation. The approval of the Human Ethics Committee of the university was obtained before starting the experiment.

2.2 Task of the main experiment

In order to build on previous work the isometric wrist flexion task of Carey and Gallwey (2002) was chosen (i.e. 10N$\pm$1N flexion force) but at a frequency of 15 exertions per minute, as used by Carey and Gallwey (2005), for periods of five minutes. This was in line with Lin et al. (1997) values of 4 and 20 motions/minute, and the 10 to 20 deviations per minute of Yen and Radwin (2000). The results of the study of Ciriello et al. (2002) revealed that mean maximum acceptable torques ranged from 14% to 24% (median of 17%) of maximum isometric torque depending on the frequency and motion. However Lin et al. used force levels of 15N and 45N. The reason for a fixed force level was that in real jobs operators would all have to exert the same force, and a relative force would be difficult to implement in a real job. These combinations of repetitive movements and force exertions are considered to be similar to those observed in some industrial assembly tasks.

2.3 Postures

Angular movements were defined as a percentage, relative to maximum Range Of Motion (ROM). ROM was the maximum range of angular deviation in degrees (in the pain free range) respective to the direction of movement of the wrist or forearm that the participant was able to make. The axes of rotation for the wrist and forearm posture are presented in Figure 1. Five levels of wrist radial/ulnar deviation were used 0%, 35% and 55% of the ROM in radial and ulnar, based on Drury's (1987) zones of wrist deviations. There were five levels of forearm rotation selected from O'Sullivan and Gallwey (2001), viz. 60% and 30% ROM supine, neutral, and 30% and 60% ROM prone. To reduce the risk of injury due to combining wrist deviation with forearm rotation, values beyond 60% ROM of forearm rotations were avoided, even though those were used by O'Sullivan and Gallwey (2001).

[Place Figure 1 about here]

2.2. Experimental Design

With five Wrist Deviations and five Forearm Rotations there were 25 combinations available in a full factorial design. Therefore 25 participants were used, and, to obviate order effects, a modified Latin square was employed to decide experimental orders. In a small number of cases, the random order was changed so that a "difficult" condition was not followed immediately by another such condition, due to the risk of injury to the participants. Replication of the whole experiment was too big a task so it was carried out one week later on only 6 participants. This was to give a measure of the residual error so that the significance of the 3-way interaction could be checked.

2.4 Apparatus

A rig was constructed to allow wrist radial/ulnar deviation and forearm rotation about its axis. As shown in Figure 2, the rig was mounted on a height adjustable table. A force meter (Biometrics E3000 Upper Limb Exerciser with pinch meter Type H400) was attached to one of the radial links of the rig, in a slot with sufficient adjustment in the radial/ulnar direction. The forearm was supported horizontally on the table with a Velcro band over it to maintain the fixed position. A computer screen in front of the participant provided information about the timing and joint angles, and displayed the discomfort scale.

[Place Figure 2 about here]

2.5 Data Collection and Control

Joint angles were measured by means of Biometrics electro-goniometers. Two separate goniometers were attached to the skin in line with the manufacturer's instructions. Signals from the electro-goniometers and the force meter were interfaced with a 333MHz PC using a National Instruments data acquisition board (PCI MIO 16XE-50). The experiment was controlled using LabVIEW-6i Virtual Instruments (VIs) displayed on the computer screen, as shown in Figure 3. The VAS for the discomfort scale was marked on the screen by the participant using the cursor. Angular movements of wrist radial/ulnar and forearm rotation were reflected in real time on the computer screen by means of horizontal sliding bars. A vertical slider bar indicated the flexion force with bands labelled at $\pm$1N about the level of 10N; an audio tone sounded, and the bar changed from green to red, if the participant's exertion went outside this range.

[Put Figure 3 about here]

2.6 Preliminary data collection

After participant briefing the experiment started with the measurement of ROMs of wrist radial/ulnar deviation and forearm prone/supine rotation. For the forearm ROM the elbow was flexed 90^0, the upper arm was close to the body (i.e. no abduction) and the wrist was at neutral in both planes. Wrist deviation was measured for the fully prone forearm with the elbow flexed 90^0 and neutral wrist in the flexion/extension direction (Carey and Gallwey, 2002). Maximum Grip strength for the fully prone forearm with a neutral wrist was measured as per Carey and Gallwey (1999). To introduce participants to scoring on the VAS, endurance time at 50% MVC grip was recorded for each participant, using a simple five-point VAS display with indicators of "No discomfort" at 1, "Medium discomfort" at 3, and "Extreme discomfort" at 5, as per Corlett and Manenica (1980). The total time to reach level 5 was recorded for use as a possible covariate to reduce the effects of differences in pain tolerance between participants (Carey and Gallwey, 1999).

2.7 Electromyography

To identify the relative contributions of the muscles to the exertions, EMG data of some forearm muscles were recorded prior to the main experiment for the twenty five postural combinations selected for the main experiment. The four muscles chosen were Flexor

Carpi Radialis (FCR), Flexor Carpi Ulnaris (FCU), Extensor Carpi Radialis Brevis (ECRB) and Extensor Carpi Ulnaris (ECU) as they were expected to be the most active surface muscles for the flexion task. Skin preparation and electrode placement procedures were conducted in accordance with the recommendations of SENIAM8 (Hermens et al., 1999). EMG signals were detected using pairs of Ag/AgCl surface electrodes positioned with an inter-electrode distance of 20 mm and 30 mm distance between pairs of electrodes of different muscles to avoid cross-talk. The minimum of 30 mm distance was kept based on the advice of the electronic engineer helping in the data acquisition, but this distance did not violate the SENIAM8 guidelines. The skin resistance at each electrode was kept below 10 k-ohms. Two EMG amplifiers (CB Sciences ETH 2001) were used, with input impedance of 10M-ohm, a CMRR of 100dB and the gain set to X1000. Butterworth band pass filters (10Hz to 500Hz) were applied and the sampling frequency set at 512Hz in LabVIEW6i, the highest possible due to equipment limitations. EMG signals were collected for 10 seconds duration at every articulation in a Latin square order to obviate order effects.

2.8 Procedure of Main Experiment

The participants sat on a fully adjustable chair at a fixed position on the floor with respect to the rig. The elbow was flexed at 90^0, the forearm horizontal, and upper arm positioned at approximately 45^0 in the coronal plane. Initially the participant read a briefing sheet and a number of questions were answered before signing the informed consent form, after which the preliminary data were collected. The participant exerted an isometric flexion force for one second during the 4-second cycle, repetitively for a five-minute duration at each articulation. The time was controlled by an analogue clock on the computer screen supplemented by a beep at the beginning and end of each exertion. At the end of each five-minute treatment the participant recorded discomfort on the 100 mm VAS anchored with labels of “no-discomfort” and “extreme-discomfort” (Figure 3). A rest of at least one minute was provided between each exertion, on the assumption that this would preclude cumulative fatigue (Carey & Gallwey, 2002). After 75 minutes participants were given a break of 30 minutes. A further 75 minutes were required for the remaining treatments.

3 Results

3.1 Ranges of Motions (ROM)

The mean ROM values for radial and ulnar deviation of the wrist, and prone and supine rotation of the forearm were 25.6^0 (SD 9.8), 42.2^0 (SD 8.06), 46^0 (SD 9.03) and 52^0 (SD 11.43) respectively.

3.2 MVC and Endurance Time

The average grip strength of the participants was 435N, with a range of 238N to 721N (SD 128.4). The mean endurance time for 50% of the maximum grip strength (MVC) was 36 seconds (range 10 to 63 seconds with SD 15.6). The data for endurance time against discomfort levels was found to be similar to other studies reported previously (Corlett and Manenica 1980, Carey and Gallwey, 1999). The time was found to be linearly related to discomfort score (i.e. five point scale from ‘1’ to ‘5’ of Corlett and Manenica 1980) with the relationship $y = 8.62\,x - 8.228$ at $R^2 = 0.99$, where ‘y’ was endurance time in seconds and ‘x’ was discomfort level between 1 and 5.

3.3 Discomfort Scores

Raw discomfort values were not normally distributed. For this reason, and to provide comparisons with previous work, the data were standardised using a min-max standardisation procedure (Gescheider, 1985) as follows:

$$\text{Standardised Discomfort Score (SDS)}_{ij} = \frac{(\text{raw data}_{ij} - \text{min. data}_j)}{(\text{max. data}_j - \text{min. data}_j)} \times 10$$

Where, raw data_{ij}: discomfort score for i^{th} treatment for j^{th} participant

min data_j: minimum discomfort value within data of the j^{th} participant

max data_j maximum discomfort value within data of the j^{th} participant

The cursor position on the 100mm scale was adjusted to a value between 0 and 10 and the mean values of these Raw Discomfort Scores (RDS) and Standardised Discomfort Score (SDS) with standard deviation for all the twenty-five conditions were plotted on a bubble diagram (Figure 4 & 5). The mean values of Raw Discomfort Score (RDS) varied from 2.43 at neutral to 5.10 at 55% ulnar deviation with 60% supine rotation of the forearm.

[Put Figure 4 about here]

[Put Figure 5 about here]

SDS values ranged from 1.8 at neutral to 7.67 at an articulation of 55% ulnar and 60% supine ROM. But SDS values were also not normally distributed and, though many transformations were tried, none of them normalised it. However the distribution of the RDS data was closer to normal, and the Log(X+1) transformation gave a normal distribution (Levene's test, p=0.371) for these Transformed Discomfort Score (TDS) values. The means and standard deviations of RDS, SDS, and TDS are presented in Table 1. The TDS data were used for all statistical analyses but first Mauchly's test of sphericity was carried out with the results shown in Table 2. Only prone/supine rotation of the forearm violated the test of sphericity (at p=0.005). The Greenhouse-Geisser epsilon correction factors of Table 2 were then used to adjust the numerator and denominator degrees of freedom in the F test by the values shown.

[Put Table 1 about here]

[Put Table 2 about here]

A repeated measures ANCOVA was performed on the TDS data using SPSS 11.3 (Table 3) with endurance time as the covariate. Endurance time was not a significant covariate (p=0.364). Only radial/ulnar deviation and forearm rotation were significant (p=0.007 and 0.001 respectively). To differentiate between the levels of these factors Student Newman Keuls (SNK) tests were used (Tables 4 and 5) on the TDS data. The neutral wrist was significantly different from 35% ROM in radial and ulnar deviation and these in turn from the 55% ROM levels. For the forearm, neutral was significantly different from a combined group of 30% ROM in prone and supine and 60% ROM prone, and these were similarly different from 60% ROM supine.

ANOVA was also performed on the data for the replication on six participants which showed no significant effect of the three-way interaction between wrist deviation, forearm rotation, and participant (p=0.308).

[Put Table 3 about here]

[Put Table 4 about here]

[Put Table 5 about here]

These points are illustrated further in Figure 6. On the whole a clear picture emerges but there are some anomalies, especially 60% ROM prone at –55% wrist radial deviation (Figure 6) and 55% ROM radial at –60% ROM prone rotation.

[Put Figure 6 about here]

In Figure 6 the level of TDS was higher for 60% supine than 60% prone. But the level of TDS was higher for 55% radial deviation at 60% prone than of 30% supine. TDS vs. forearm rotation shows greater change in the supine direction than the prone direction. The change in TDS for forearm rotation from 30% prone ROM to 30% supine was almost the same for both 35% ulnar and 55% radial ROM.

3.4 Mathematical Modelling

Regression analysis was performed on the TDS data (Figure 6), which gave the set of quadratic equations presented in Table 6. Using these equations, iso-discomfort contours were plotted with respect to angular deviations in % ROM (Figure 7) to predict the levels of discomfort using the antilog values of the data from the TDS regression equations. These contours demonstrate that the combination of supine rotation with ulnar deviation led to a greater increase in discomfort than the other combinations of wrist deviation and forearm rotation angle (%ROM). To show this in another form a 3D plot of these data is shown in Figure 8. It emphasises the steep rise in discomfort in the corners of Figure 7.

[Put Table 6 about here]

[Put Figure 7 about here]

[Put Figure 8 about here]

3.5 EMG Analysis

Root Mean Square (RMS) values were calculated over each interval of 500ms (256 data points with 50% overlap) during the 10-second recording for each condition. Maximum RMS values of each condition were normalised for each muscle activity for each participant in percentage terms according to the formula of Strasser (2001) reproduced below.

$$\text{Normalised EMG\%} = \frac{rmsEMG_i - rmsEMG_{min}}{rmsEMG_{max} - rmsEMG_{min}} \times 100\ \% \qquad \text{where, } j = 1 \text{ to } n$$

and n = number of treatments in the experiment

$rmsEMG_i$	maximum RMS EMG calculated from the recording of respective muscle for the j^{th} treatment j = 1 to n $rmsEMG_{min}$ maximum RMS EMG calculated from the recording of respective muscle during relaxed condition of the wrist and forearm system (without any flexion or other force)
$rmsEMG_{min}$	maximum RMS EMG calculated from the recording of respective muscle during maximum possible flexion exertion

These normalised EMG data were used for further analysis. Analysis of variance (ANOVA) was used on the EMG activity of each muscle with the data transformed to Log(X+1) values to get a normal distribution, verified by Levene's test (p=0.96, 0.009, 0.911, and 0.179 for the FCR, FCU, ECRB and ECU respectively). The results of

ANOVAs are presented in Table 7 and these are summarised in Table 8. Data from the FCU muscle violated normality (Levene's test) but even so the graphs showed a nearly normal distribution for Log(X+1) transformed data.

Student Newman Keuls post ANOVA analyses were performed on the EMG data and the results of groupings of levels of wrist deviation and forearm rotation are presented Table 8. For the effects of wrist deviation two sets of groups were identified for the FCR, ECRB and ECU, and three groups were identified for the FCU. The results demonstrate the significant effect of radial deviation on activity of the FCU, ECRB and ECU, but also that ulnar deviation did not have a significant effect on the FCR. For the effects of forearm rotation on EMG activity two groups were identified for the FCU and ECU but no groups were identified for both the FCR which was significant in the ANOVA (Table 7, $p<0.04$) and the ECRB which was not significant in the ANOVA ($p<0.98$).

[Put Table 7 about here]

[Put Table 8 about here]

The mean activity in FCR increased with rotation from neutral in both supine and prone rotation (Figure 9), whereas for FCU it increased with supine rotation but was substantially constant on the prone side. In both, there was little change in activity between 30% prone and 30% supine, but at 60% supine the change was comparatively large. In Figure 10 it can be seen that the activity for FCR dropped more or less continuously from 60% radial to 60% ulnar, but for FCU there was little change on the radial side and a steady increase from neutral to 60% ulnar. In contrast ECRB and ECU were effectively constant at a few per cent on the radial side and increased slightly on the ulnar side.

[Put Figure 9 about here]
[Put Figure 10 about here]

4 Discussion

4.1 Endurance time

The linear relationship of endurance time with discomfort levels is similar to other findings such as the increase of discomfort with the percentage of maximum endurance time reported by Corlett and Manenica (1980). They obtained a linear pattern with 30%, 50% and 70% MVC of a ‘push’ activity. They concluded that for equal proportions of the maximum holding time the pain levels are the same. Putz-Anderson and Galinsky (1993) also found a linear increase in discomfort for three verbal levels (moderate, somewhat strong and strong) against time for 10%, 20% and 30% of the MVC. But in the latter it is arguable whether these constitute a ratio scale.

That endurance time was not a significant covariate is probably because it was measured on a static power grip, whereas the discomfort recorded was for a repetitive flexion task. Carey and Gallwey (1999) introduced the idea of using grip endurance time as a covariate because they obtained significance and it was hoped that this could form a standard test for pain tolerance. Now the question arises whether it is task specific or not? In a previous study Khan et al. (2003) found grip endurance time was a significant covariate ($p=0.002$) but the task combined wrist flexion with gripping.

Hence, a supplementary experiment was performed to compare grip endurance time with flexion force endurance. It employed twelve participants and measured their endurance times for 50% MVC of both grip and wrist flexion force on a five-point discomfort scale. There was no significant difference ($p>0.65$) in the times. Based on these findings it can be inferred that the question is still open whether task specific flexion endurance time can possibly be used to eliminate the differences between participants or not. Another possible reason is that the participants may have had homogeneous muscle fibre & tendon properties. Van Dieen and Oude Vrielink (1994) indicated that differences between endurance curves for specific exertions could be largely explained by muscle composition.

4.2 Discomfort

An aim of this study was to extend the work of Carey and Gallwey (2002 and 2005) and it is interesting to note that at 55%ROM radial deviation they recorded the same SDS of 4.07 but at 55%ROM ulnar this study gave a value of 3.71 against their figure of 1.65 (Table 9). This latter figure must be regarded with some caution as it seems to be far too low but the higher figure of the present study could be due to some degree of cumulative pain and fatigue. However, with the addition of forearm rotation, for 30%ROM in supine with 55% ROM radial and ulnar deviation, the values of SDS rose to 4.91 and 5.61 respectively. Similarly, at still greater rotation angles in either direction, the SDS values increased again. Hence it is clear that the addition of forearm rotation had an increased effect on discomfort.

[Put Table 9 about here]

Carey and Gallwey (2002) also found a significant effect for wrist deviation ($p<0.01$) on discomfort but this was for the forearm fully prone. This study also recorded greater discomfort for radial deviation with the prone forearm but found that the pattern changed considerably between the neutral and supine forearm. For Drury et al. (1985) radial deviation proved worse than ulnar deviation for the same angles. That contradicts the present findings where ulnar deviation was worse than radial. But Drury et al. (1985) recorded discomfort at fixed absolute angular displacements in a different task and with different elbow flexion angles ($>90^0$), whereas in the present study displacements were in terms of relative % ROM. Hence the results of Drury et al. (1985), that discomfort will be greater in radial than ulnar, may not be true if deviation is measured in % ROM.

O'Sullivan and Gallwey (2001) obtained higher SDS values for the supine forearm but for a different type of task (forearm torquing). In supine rotation they reported SDS of around 1.5 units higher than the prone value at 75% ROM. Both studies indicate a significant forearm rotation effect for different types of exertion but further studies are needed to examine other exertions typical of industrial work to model these effects more accurately.

The study of Keir et al. (2007) provided the guidelines for wrist deviation based on Carpal Tunnel Pressure (CTP) (mmHg). The study showed that CTP increased from 13mmHg at neutral wrist to 25mmHg for radial deviation of 20^0, and slightly higher for 20^0 ulnar deviation of the wrist. This increase in CTP could be one of the causes of increased discomfort score recorded in the present study for the deviated wrist.

4.3 EMG activity

While discomfort data for specific parts of the forearm were not collected the EMG data collected before the main experiment provides some insight into the distribution of musculoskeletal loading across the different postures. EMG activity was significantly higher in the FCR for radial deviation and lower in ulnar deviation, although not significantly. However for the other muscles (FCU, ECU & ECRB) the EMG activity was higher in ulnar deviation compared to radial. This trend was also evident in the discomfort data where average values were higher for same proportion ulnar ROM postures over radial. The increase in mean EMG activity for the forearm muscles in deviated prone and supine postures was also accompanied by increased mean discomfort scores. Elevated EMG activity in deviated postures is probably indicative of an increase in muscle activity due to the compromised biomechanical advantage of the muscle moment arms in deviated postures.

Khan et al. (2003) reported a decrease in grip strength with flexion of the wrist and also an increase in discomfort. So it is possible that a change in flexion MVC could be the cause of the increased discomfort at non-neutral articulations. Hence the actual percentage of MVC exerted at these positions would be greater than the figure presumed. For that reason a supplementary experiment examined the change in flexion MVC with wrist deviation and forearm rotation. Wrist flexion/extension was significant but forearm rotation was not. Similarly the locations of discomfort in the forearm, wrist or hand needed to be known; this was also examined in the supplementary experiment using a Body Part Discomfort Map. For the flexion endurance test there was discomfort on both the flexion and extension sides of the forearm, which supports the EMG data for the two flexors (FCR & FCU) and two extensors (ECRB & ECU).

5 Conclusions

Grip endurance time was not a significant covariate (p=0.364) and had no significant linear relationship with mean discomfort score with respect to participant (R^2=0.028, p=0.42). Hence grip endurance time was not a suitable covariate to reduce subjective differences in discomfort for this experiment. The main effects of wrist deviation and forearm rotation were significant (p=0.007 and 0.001 respectively) on discomfort but the interaction was not significant (p=0.966). The three-way interaction between wrist deviation, forearm rotation, and participant was also not found significant (p=0.308). Discomfort prediction and iso-discomfort contours (R^2 =0.90) were developed to predict discomfort with respect to forearm rotation and wrist deviation in terms of %ROM. For example, the risk of injury at 55%ROM wrist deviation with 60%ROM forearm rotation is quite high. The high discomfort scores for the combined wrist deviation and forearm rotation conditions above 30%ROMs are indicative of a synergistic relationship, and the regression models accurately project this. However, care is needed in industry that such posture combinations are avoided so that exposure to high-risk levels is avoided.

Acknowledgement

The research in this paper was funded by the MIRTH project of the European Union “Growth” Programme (Musculoskeletal Injuries Reduction Tool for Health and safety, MIRTH-CT-2001-00574). The authors are thankful to the reviewers and editor for many helpful comments.

References

AARAS, A., DAINOFF, M., RO, O. and THORESEN, M., 2002, Can a more neutral position of the forearm when operating a computer mouse reduce the pain level for VDU operators? *International Journal of Industrial Ergonomics*, **30**, 307-324.

AARAS, A., WESTGAAD, R.H. and STRANDEN, E., 1988, Postural load as an indicator of postural load and muscular injury in occupational work situations, *Ergonomics*, **31**, 915-933.

ARMSTRONG, T. J. and CHAFFIN, D.B., 1978, An investigation of the relationship between displacements of the finger and wrist joints and the extrinsic finger flexor tendons, *Journal of Biomechanics*, **11**, 119-128.

BERNARD, B.P. (Ed.), 1997, *Musculoskeletal Disorders and Workplace Factors*, National Institute for Occupational Safety and Health, (Cincinnatti).

BLADER, S., BARCK-HOLST, U., DANIELSSON, S., FERHM, E., KALPAMMA, M., LEIJON, M. and MARKHEDE, G., 1991, Neck and shoulder complaints among sewing-machine operators: a study concerning frequency, symptomatology and dysfunction, *Applied Ergonomics*, **22 (4)**, 251-257.

BLS, 1995, Workplace injuries and illnesses in 1994**,** U.S. (Department of Labour, Washington, DC), USDL 95 – 508.

CAREY, E.J. and GALLWEY, T.J., 1999, *Discomfort prediction from postural deviations of the wrist*, In: M.A. Hanson, E.J. Lovesey and S.A. Robertson (Eds.), *Contemporary Ergonomics*, (Taylor and Francis, London), 296-300.

CAREY, E.J. and GALLWEY, T.J., 2002, Effects of wrist posture, pace and exertion on discomfort, *International Journal of Industrial Ergonomics*, **29**, 85 – 94.

CAREY, E.J. and GALLWEY, T.J., 2005, Wrist discomfort levels for combined movements at constant force and repetition rate, *Ergonomics*, **48**, 171-186.

CIRIELLO, V.M., WEBSTER, B.R., and DEMPSEY, P.G., 2002, Maximal acceptable torques of highly repetitive screw driving, ulnar deviation, and handgrip tasks for 7-hour workdays, *American Industrial Hygiene Association*, **63**, 594-604.

CORLETT, E.N. and BISHOP, R.P., 1976, A technique for assessing postural discomfort, *Ergonomics*, **19**, 175-182.

CORLETT, E.N., and MANENICA, I., 1980, The effects of measurement of working postures, *Applied Ergonomics*, **11**, 7-16.

DIMBERG, L., 1987, The prevalence and causation of tennis elbow (Lateral epicondylitis) in a population of workers in an engineering industry, *Ergonomics*, **30**, 573-580.

DRURY, C.G., 1987, A biomechanical evaluation of the repetitive motion injury potential of industrial jobs, *Seminars in Occupational Medicine*, **2**, 41-49.

DRURY, C.G., BEGBIE, K., ULATE, C. and DEEB, J.M., 1985, Experiments on wrist deviation in manual materials handling, *Ergonomics*, **28 (3)**, 577-589.

ESTILL, C.F., and KROEMER, K.H.E., 1998, Evaluation of supermarket bagging using a wrist motion monitor, *Human Factors*, **40 (4)**, 624-632.

GENAIDY, A.M. and KARWOWSKI, W., 1993, The effects of neutral posture deviation on perceived joint discomfort ratings in sitting and standing postures, *Ergonomics*, **36**, 785-792.

GESCHEIDER, G.A. (Ed.), 1985. Psychophysics – Method, Theory, and Application. 2nd Ed., (Lawrence Earlbaum, Hillsdale, NJ).

HAGBERG, M., SILVERSTEIN, B., WELLS, R., SMITH, M., HENDRICK, CARAYON, P. and PERUSSE, M., 1995, *Work Related Musculoskeletal Disorders: A Reference Book of Prevention*, (Taylor & Francis, London).

HASHEMI, L., WEBSTER, B.S., CLANCY, E.A. and COURTNEY, T.K., 1998, Length of disability and cost of work-related musculoskeletal disorders of the upper extremity, *Journal of Occupational Environment and Medicine*, **40**, 261-269.

HERBERT, R., DROPKIN, J., WARREN, N., SIVIN, D., DOUCETTE, J., KELLOGG, L., BARDIN, J., KASS, D. and ZOLOTH, S., 2001, Impact of joint labor-management ergonomics program on upper extremity musculoskeletal symptoms among garment workers, *Applied Ergonomics*, **32**, 453-460.

HERMENS, H.J., FRERIKS, B., Merletti, R., HÄGG, G., STEGEMAN, D.F., BLOK, J., RAU, G., DISSELHORST-KLUG, C., 1999, *SENIAM 8: European Recommendations for Surface ElectroMyoGraphy*, (Roessingh Research and Development, The Netherlands, ISBN 90-75452-15-2).

KHAN, A. A., GALLWEY, T.J. and O'SULLIVAN, L., 2003, Effects of grip force when combined with wrist flexion and frequency of exertions, *Quality of Work and Products in Enterprises of the Future*, H. Strasser, K. Kluth, H. Rausch and H. Bubb (Eds.), (Proceedings of International Ergonomics Conference, Ergonomica Verlag, Stuttgart, ISBN 3-935089-68-6), 391-394.

Keir, P. J., Bach, J. M., Hudes, M., and Rempel, D. M., 2007, Guidelines for wrist posture based on Carpal Tunnel Pressure Thresholds, Human Factors, 49 (1), 88–99.

KLEIN, M.G. and FERNANDEZ, J.E., 1997, The effects of posture, duration, and force on pinching frequency, *International Journal of Industrial Ergonomics*, **20**, 267-275.

LABUS, J.S., KEEFE, F.J. and JENSEN, M.P., 2003, Self reports of pain intensity and direct observations of pain behavior: when are they correlated? *Pain*, **102**, 109-124.

LIN, M.L., RADWIN R.G., and SNOOK, S.H., 1997, A single metric for quantifying biomechanical stress in repetitive motions and exertions, *Ergonomics*, **40 (5),** 543-558.

MUKHOPADHYAY, P., GALLWEY, T. and O'SULLIVAN, L.W., 2003, Effect of grip force and shoulder abduction angles in repetitive clockwise forearm pronation/supination movements, *Quality of Work and Products in Enterprises of the Future*, H. Strasser, K. Kluth, H. Rausch and H. Bubb (Eds.), (Proceedings of International Ergonomics Conference, Ergonomica Verlag, Stuttgart, ISBN 3-935089-68-6), 81-88.

O'SULLIVAN, L.W. and GALLWEY, T.J., 2001, Forearm discomfort for repeated isometric torque exertions on pronation and supination. In: M.A. Hanson, E.J. Lovesey and S.A. Robertson, (Eds.), *Contemporary Ergonomics*, (Proceedings of The Ergonomics Society Annual Conference, Taylor and Francis, London), 79-83.

PUTZ-ANDERSON, V., 1988, *Cumulative Trauma Disorders: a Manual for Musculoskeletal Diseases of the Upper Limbs*, (Taylor and Francis, London).

PUTZ-ANDERSON, V. and GALINSKY, T.L., 1993, Psychophysically determined work durations for limiting shoulder girdle fatigue from elevated manual work, *International Journal of Industrial Ergonomics*, **11**, 19-28.

RANNEY, D., WELLS, R. and MOORE, A., 1995, Upper limb musculoskeletal disorders in highly repetitive industries: precise anatomical physical findings, *Ergonomics*, **38 (7)**, 1408-1423.

SILVERSTEIN, B.A., 1998, Claims incidence of work related disorders of the upper extremities: Washington State 1987-1995, *Public Health*, **88**, 1827-1833.

SILVERSTEIN, B.A., FINE, L.J. and ARMSTRONG, T.J., 1986, Hand wrist cumulative trauma disorders in industry, *British Journal of Industrial Medicine*, **43**, 779-784.

SNOOK, S.H., VAILLANCOURT, D.R., CIRIELLO, V.M. and WEBSTER, B.S., 1995, Psychophysical studies of repetitive wrist flexion and extension, *Ergonomics*, **38 (7)**, 1488-1507.

SNOOK, S.H., VAILLANCOURT, D.R., CIRIELLO, V.M. and WEBSTER, B.S., 1997, Maximum acceptable forces for repetitive ulnar deviation of the wrist, *American Industrial Hygiene Association Journal*, **58**, 509-517.

STRASSER, H., 2001, Electromyography: Methods and techniques, In: *International Encyclopaedia of Ergonomics and Human Factors*, W. Karwowski (Ed.), (Taylor and Francis, London), **3**, 1801-1804.

TERREL, R. and PURSWELL, J., 1976, The influence of forearm and wrist orientation on static grip strength as a design criterion for hand tools, *Proceedings of the International Ergonomics Association Congress*, (IEA College Park, Maryland), 28-32.

VAN DIEEN, J.H. and OUDE VRIELINK, H.H.E., 1994, The use of the relation between relative force and endurance time, *Ergonomics*, **37**, 231-243.

YEN, T.Y., and RADWIN, R.G., 2000, Comparison between using spectral analysis of electrogoniometer data and observational analysis to quantify repetitive motion and ergonomics changes in cyclical industrial work, *Ergonomics*, **43**, 106-132.

Figure Captions

Figure 1 Postural definitions of wrist and forearm rotation and axes relevant to present Study

Figure 2 Experimental rig for recording of EMG activity

Figure 3 LABVIEW screen shot of main experiment

Figure 4 Bubble plots for Raw Discomfort Score with standard deviation

Figure 5 Bubble plots for Transformed Discomfort Score (TDS) with standard deviation

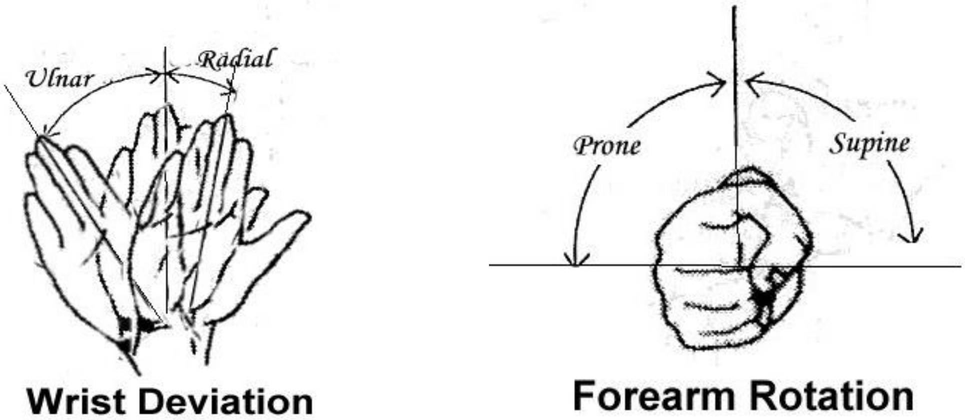
Figure 6 Transformed discomfort score vs. Wrist deviation (radial/ulnar) at prone and supine rotations

Figure 7 Iso-Discomfort Contours (antiLogTDS-1) for %ROM of wrist deviation and forearm rotation

Figure 8 3D representation of iso-discomfort contours (antiLogTDS-1)

Figure 9 Mean EMG activities of muscles vs. forearm rotation

Figure 10 Mean EMG activities of muscles vs. wrist deviation


Ulnar
Radial
Wrist Deviation
Prone
Supine
Forearm Rotation
Figure 1

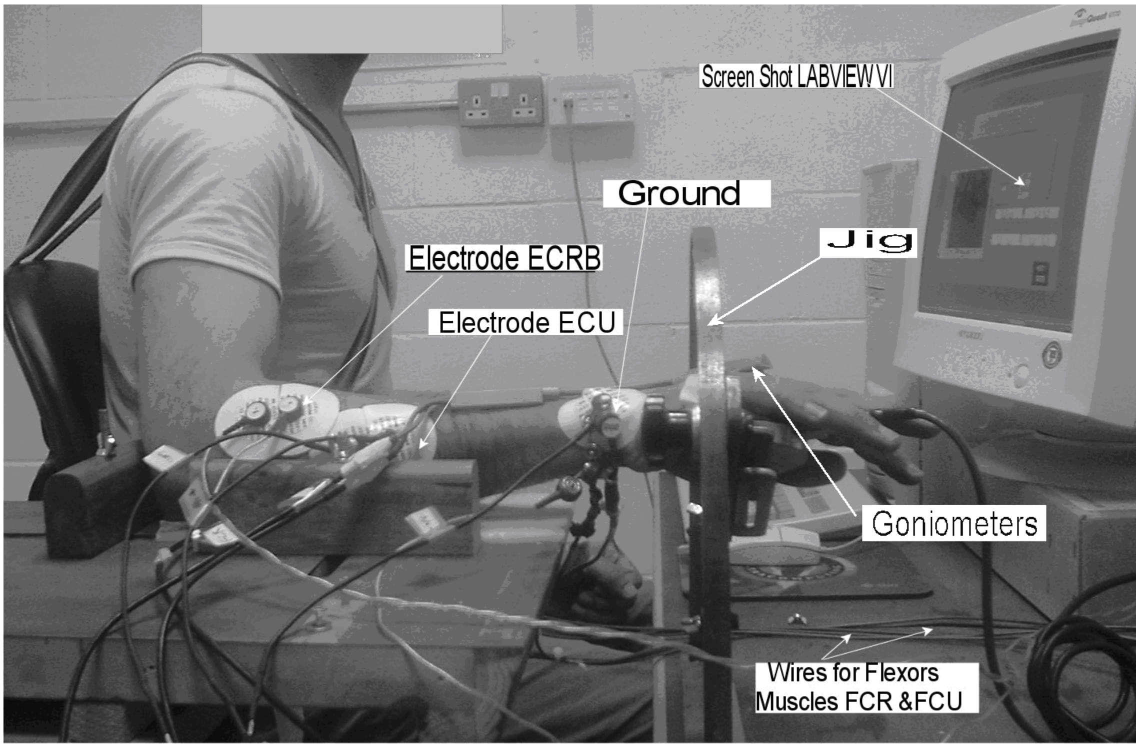

Screen Shot LABVIEW VI
Ground
Jig
Electrode ECRB
Electrode ECU
Goniometers
Wires for Flexors
Muscles FCR &FCU

Figure 2

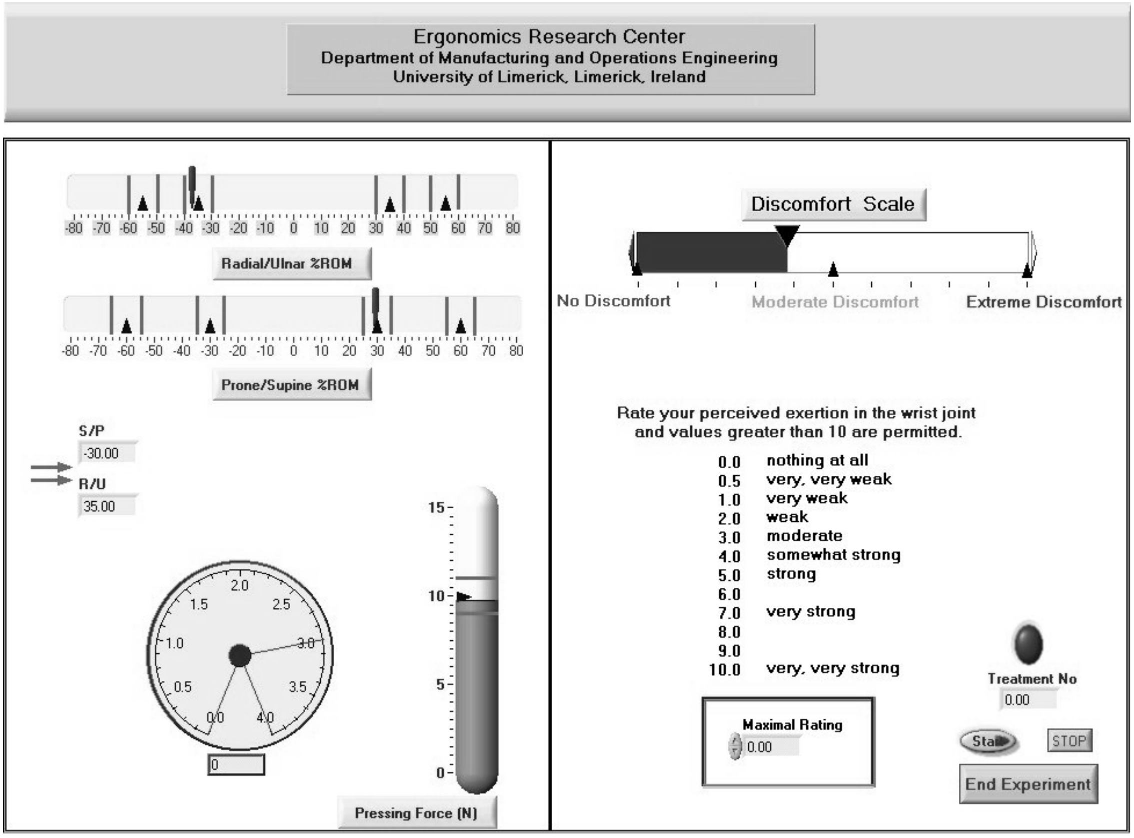
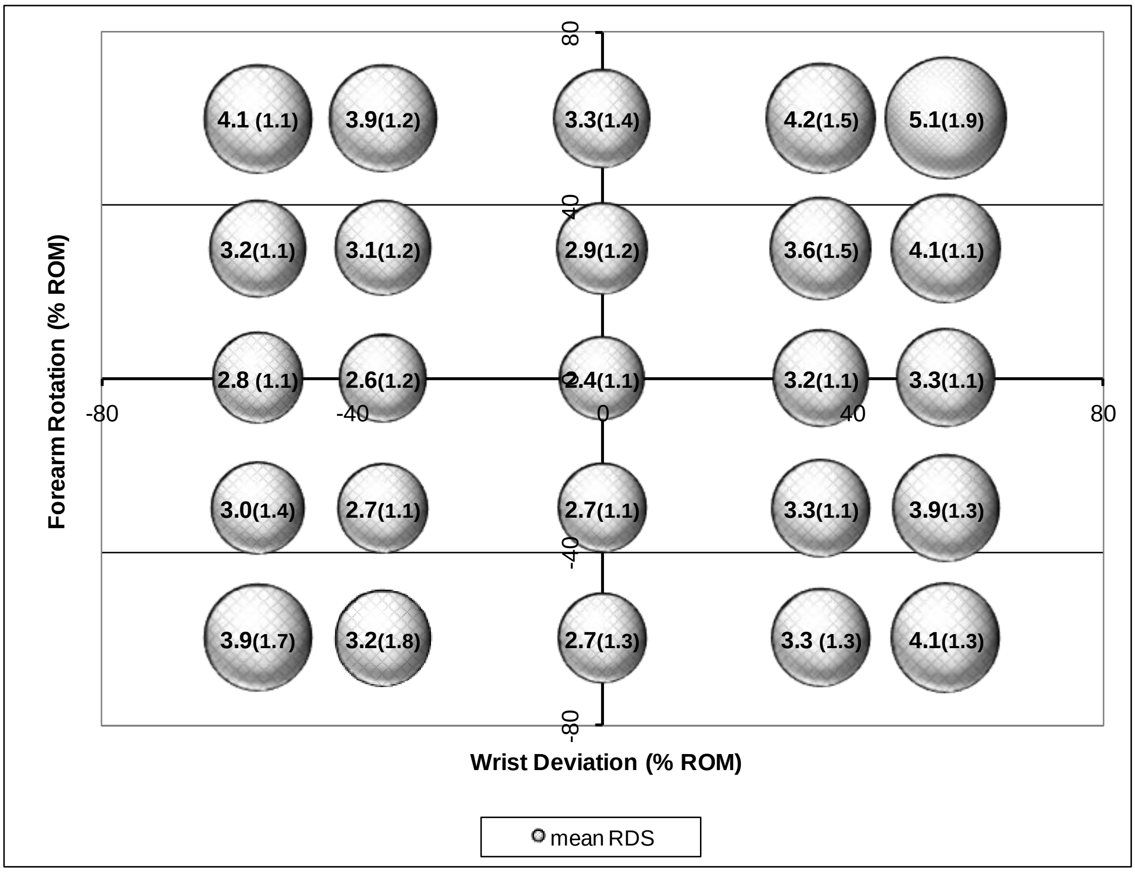

Ergonomics Research Center
Department of Manufacturing and Operations Engineering
University of Limerick, Limerick, Ireland
Radial/Ulnar %ROM
Prone/Supine %ROM
S/P
-30.00
R/U
35.00
Pressing Force (N)
Discomfort Scale
No Discomfort
Moderate Discomfort
Extreme Discomfort
Rate your perceived exertion in the wrist joint
and values greater than 10 are permitted.
0.0 nothing at all
0.5 very, very weak
1.0 very weak
2.0 weak
3.0 moderate
4.0 somewhat strong
5.0 strong
6.0
7.0 very strong
8.0
9.0
10.0 very, very strong
Treatment No
Maximal Rating
STOP
End Experiment

Figure 3



4.1 (1.1)
3.9(1.2)
3.3(1.4)
4.2(1.5)
5.1(1.9)
3.2(1.1)
3.1(1.2)
2.9(1.2)
3.6(1.5)
4.1(1.1)
2.8 (1.1)
2.6(1.2)
2.4(1.1)
3.2(1.1)
3.3(1.1)
3.0(1.4)
2.7(1.1)
2.7(1.1)
3.3(1.1)
3.9(1.3)
3.9(1.7)
3.2(1.8)
2.7(1.3)
3.3 (1.3)
4.1(1.3)
80
40
0
-40
-80
-80
-40
0
40
80
Forearm Rotation (% ROM)
Wrist Deviation (% ROM)
mean RDS

Figure 4

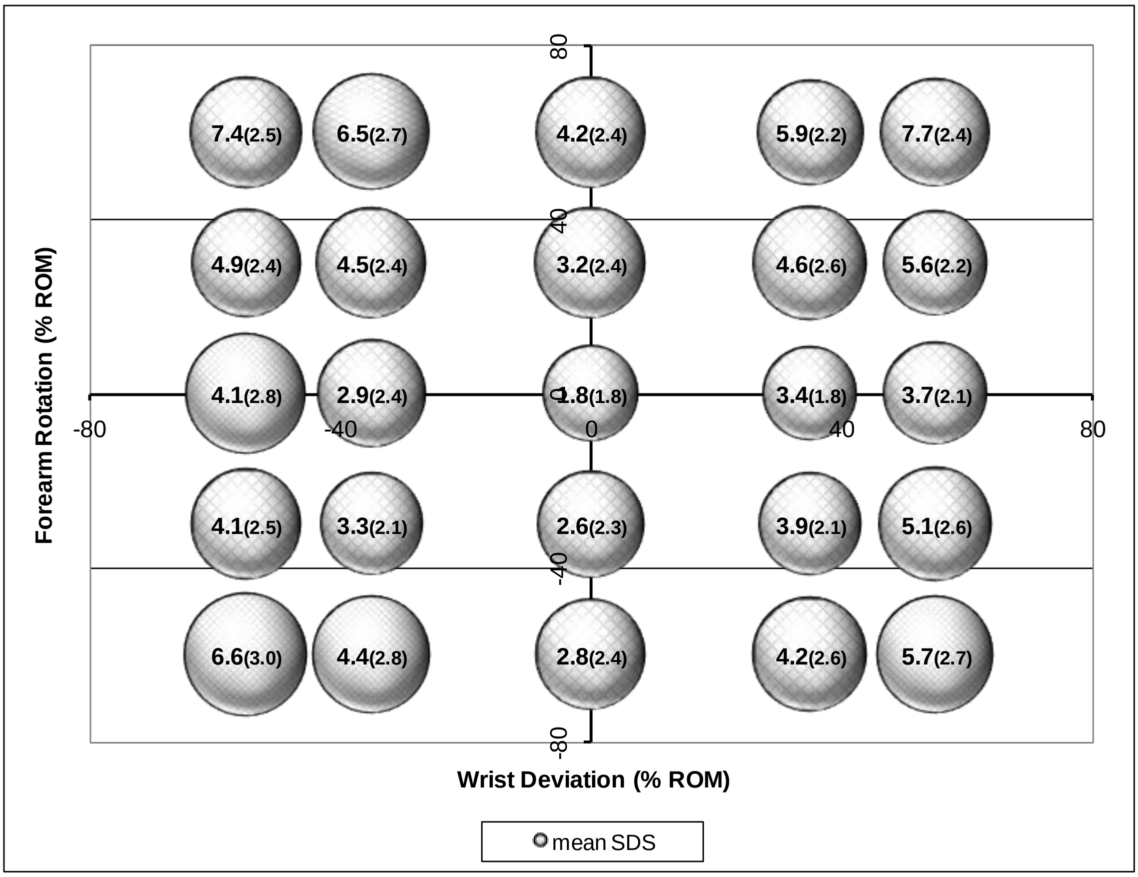
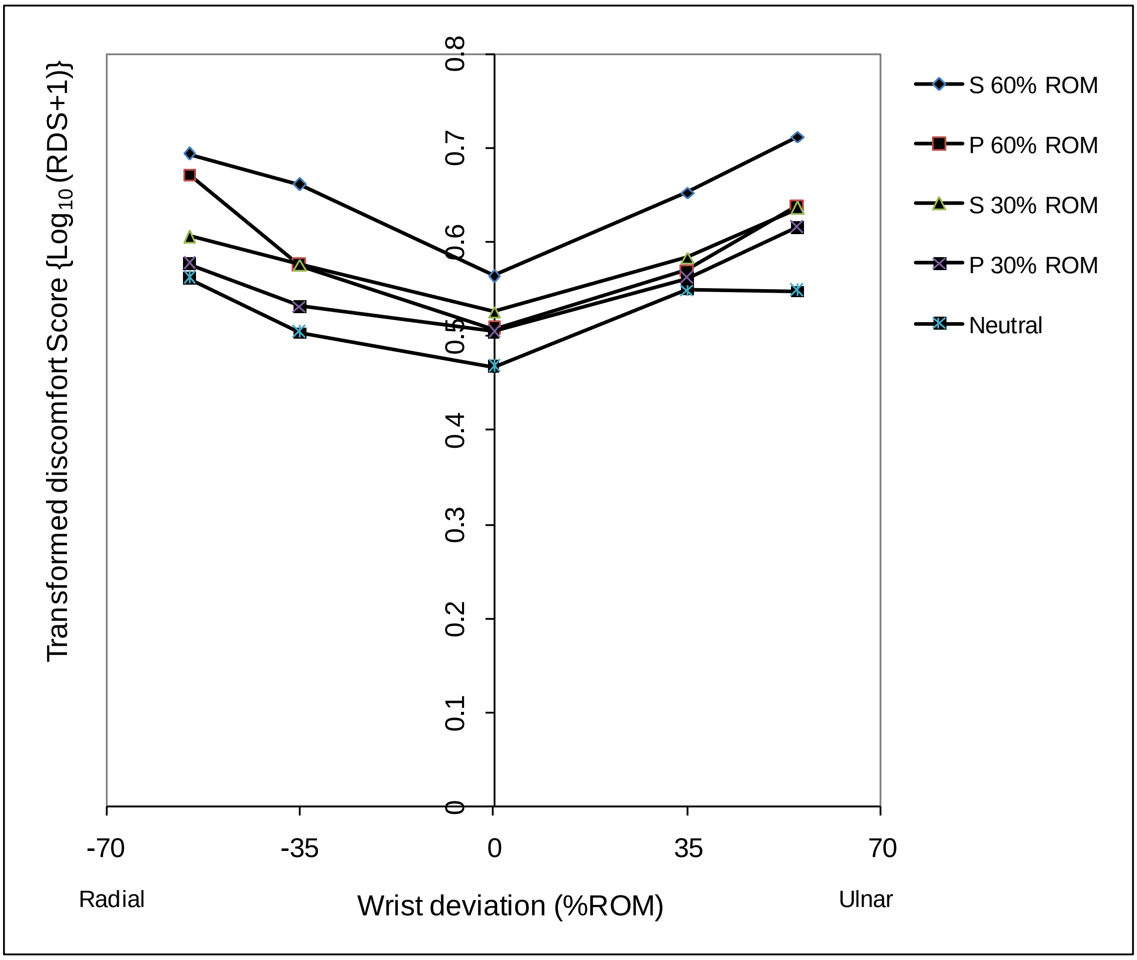

7.4(2.5)
6.5(2.7)
4.2(2.4)
5.9(2.2)
7.7(2.4)
4.9(2.4)
4.5(2.4)
3.2(2.4)
4.6(2.6)
5.6(2.2)
4.1(2.8)
2.9(2.4)
1.8(1.8)
3.4(1.8)
3.7(2.1)
4.1(2.5)
3.3(2.1)
2.6(2.3)
3.9(2.1)
5.1(2.6)
6.6(3.0)
4.4(2.8)
2.8(2.4)
4.2(2.6)
5.7(2.7)
80
40
0
-40
-80
-80
-40
0
40
80
Forearm Rotation (% ROM)
Wrist Deviation (% ROM)
mean SDS

Figure 5



Transformed discomfort Score {Log10 (RDS+1)}
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-70
-35
0
35
70
Radial
Wrist deviation (%ROM)
Ulnar
S 60% ROM
P 60% ROM
S 30% ROM
P 30% ROM
Neutral

Figure 6

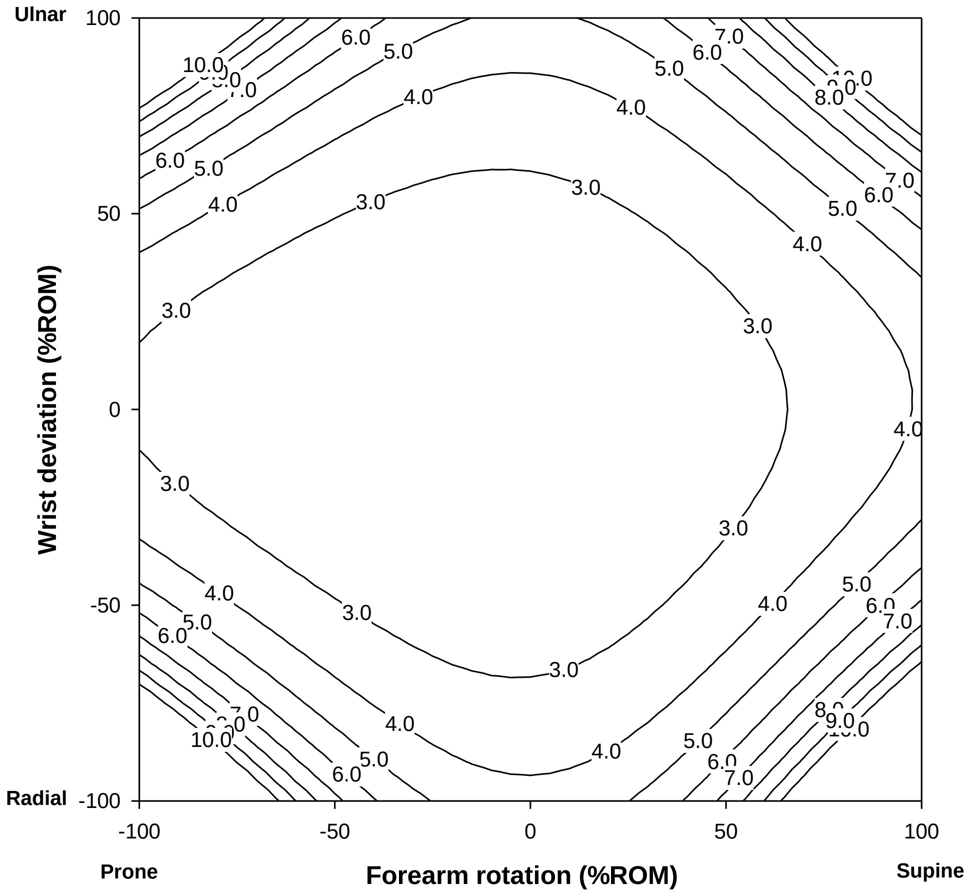

Ulnar
Radial
Prone
Supine
Wrist deviation (%ROM)
Forearm rotation (%ROM)
100
50
0
-50
-100
-100
-50
0
50
100
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

Figure 7

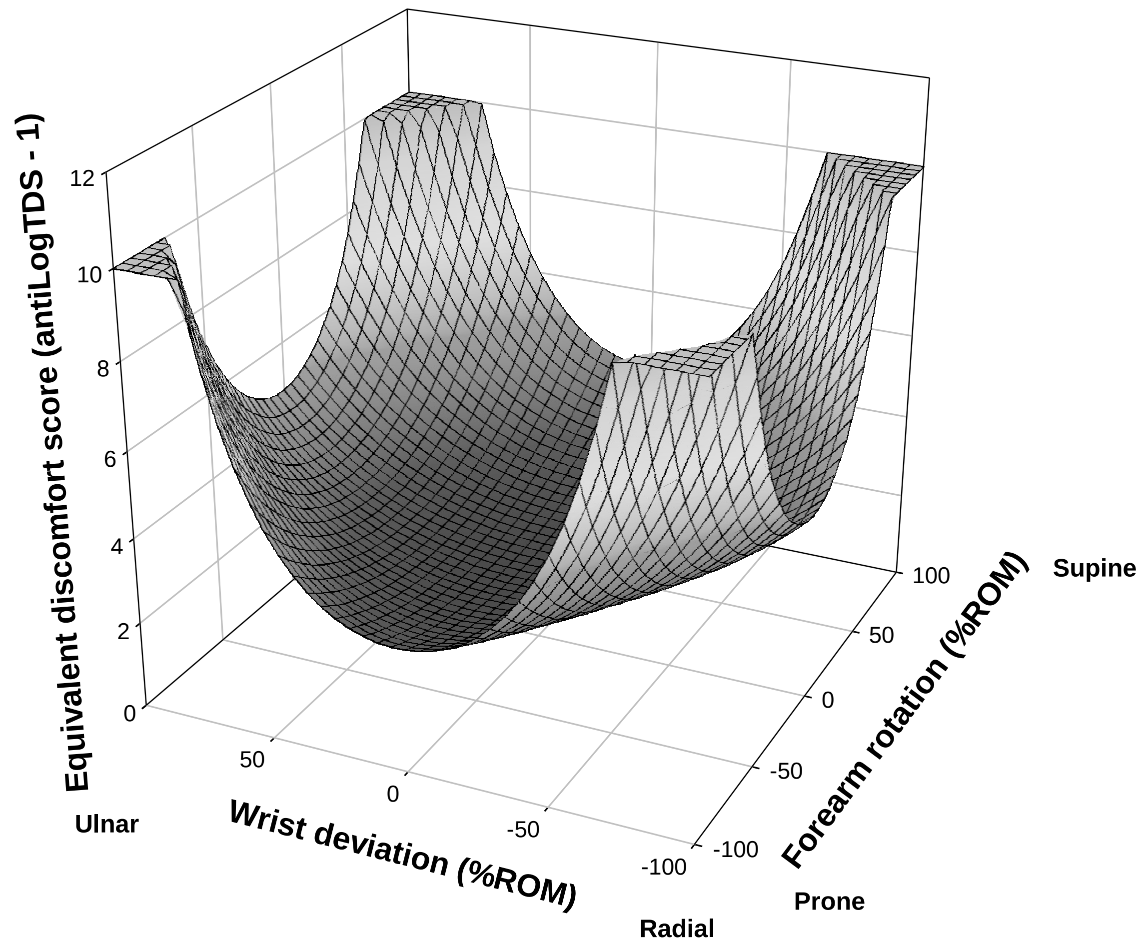
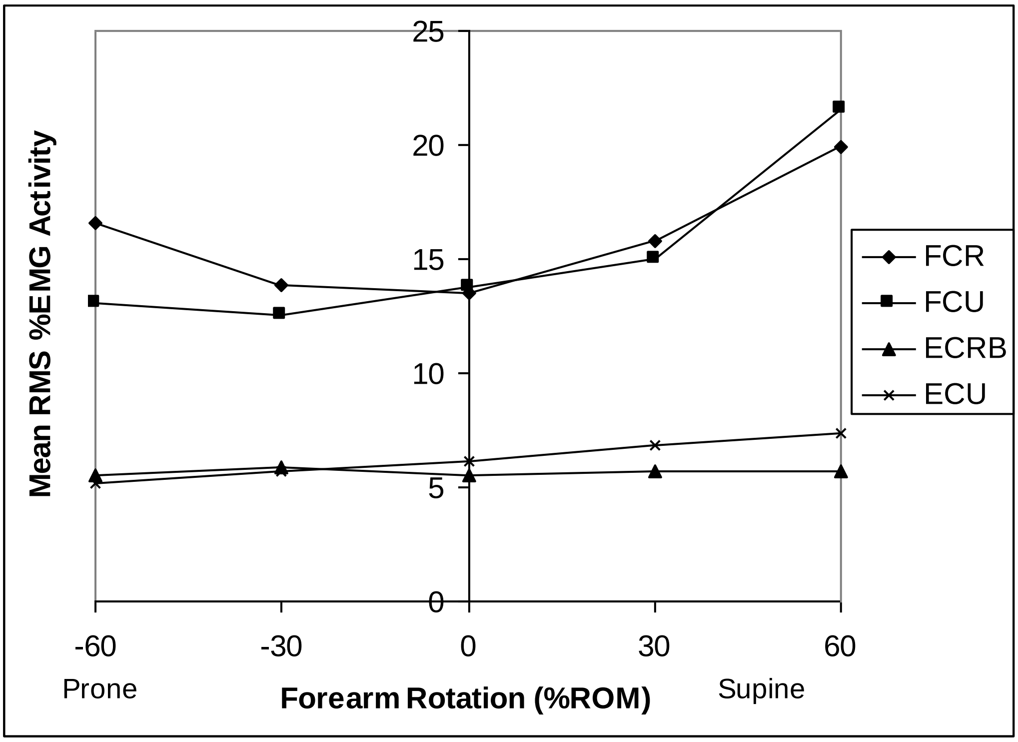
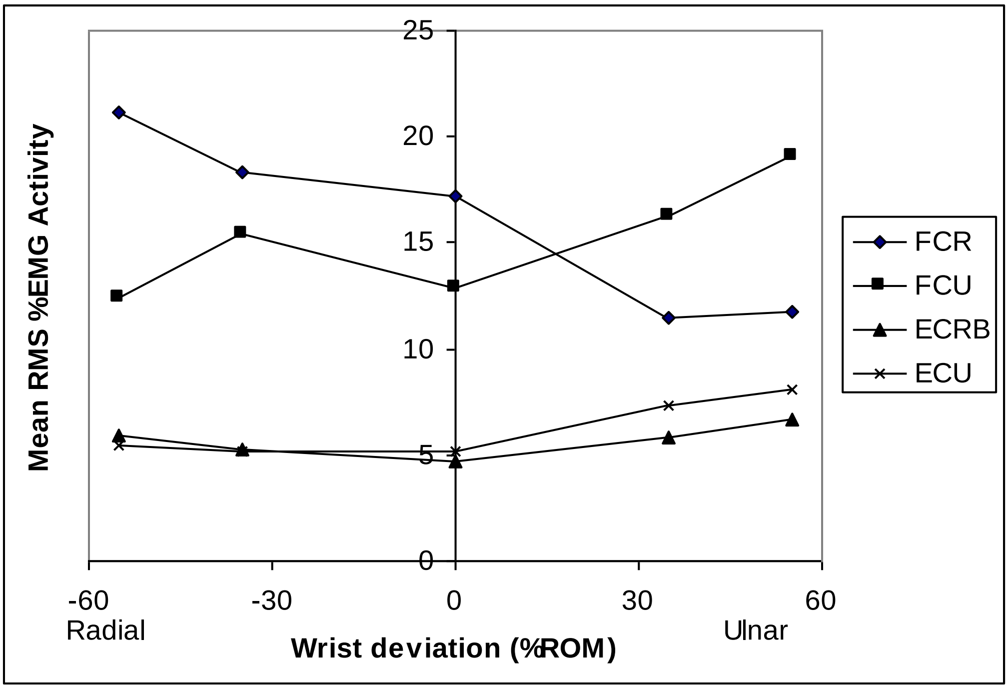

Equivalent discomfort score (antiLogTDS - 1)
12
10
8
6
4
2
0
50
0
-50
-100
Ulnar
Wrist deviation (%ROM)
Radial
100
50
0
-50
-100
Supine
Forearm rotation (%ROM)
Prone

Figure 8



Mean RMS %EMG Activity
25
20
15
10
5
0
-60
-30
0
30
60
Prone
Forearm Rotation (%ROM)
Supine
FCR
FCU
ECRB
ECU

Figure 9



Mean RMS %EMG Activity
25
20
15
10
5
0
-60
-30
0
30
60
Radial
Ulnar
Wrist deviation (%ROM)
FCR
FCU
ECRB
ECU

Figure 10

List of Tables

Table 1: The data of raw discomfort score (RDS), standardised discomfort score (SDS) and transformed discomfort score (TDS) at different levels of wrist deviation (%ROM) and forearm rotation (%ROM).

Wrist deviation (%ROM)	Forearm rotation (%ROM)	RDS		SDS		TDS	
		Mean	SD	Mean	SD	Mean	SD
-55	-60	3.97	1.67	6.61	3.01	0.67	0.15
-55	-30	2.99	1.38	4.20	2.46	0.57	0.14
-55	0	2.82	1.15	4.07	2.84	0.56	0.14
-55	30	3.19	1.15	4.91	2.38	0.60	0.12
-55	60	4.05	1.07	7.36	2.53	0.70	0.11
-35	-60	3.12	1.79	4.39	2.77	0.57	0.19
-35	-30	2.57	1.14	3.23	2.07	0.53	0.13
-35	0	2.38	1.20	2.76	2.36	0.49	0.14
-35	30	2.95	1.20	4.38	2.43	0.58	0.13
-35	60	3.72	1.24	6.45	2.69	0.67	0.11
0	-60	2.44	1.31	2.83	2.43	0.51	0.16
0	-30	2.39	1.14	2.62	2.27	0.50	0.15
0	0	2.09	1.11	1.80	1.80	0.46	0.13
0	30	2.54	1.16	3.21	2.45	0.53	0.15
0	60	2.91	1.37	4.15	2.43	0.56	0.16
35	-60	2.94	1.30	4.20	2.62	0.58	0.17
35	-30	2.83	1.13	3.87	2.10	0.56	0.14
35	0	2.69	1.10	3.41	1.78	0.55	0.13
35	30	3.10	1.55	4.60	2.60	0.58	0.16
35	60	3.72	1.53	5.94	2.24	0.65	0.14
55	-60	3.53	1.28	5.68	2.71	0.64	0.13
55	-30	3.32	1.32	5.11	2.59	0.62	0.14
55	0	2.70	1.14	3.71	2.12	0.55	0.14
55	30	3.45	1.08	5.61	2.17	0.64	0.11
55	60	4.46	1.90	7.67	2.38	0.71	0.15

Table 2. Mauchly's Test of Sphericity

Within Participants Effect	Mauchly's W	Approx. Chi-Square	Df	Sig.	Epsilon		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
R/U	0.715	9.179	9	0.422	0.848	1.000	0.250
S/P	0.420	23.789	9	0.005	0.757	0.885	0.250
R/U * S/P	0.001	155.692	135	0.153	0.556	0.851	0.0625

Table 3. Repeated measures ANCOVA on TDS data using Greenhouse-Geisser correction of Sphericity

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
END.Time (Covariate)	19.275	1.0	19.275	0.849	0.364
Wrist deviation (R/U)	0.223	3.430	0.06493	4.016	0.007
R/U * END.Time	0.01337	3.430	0.003897	0.241	0.891
Forearm Rotation (S/P)	0.277	2.907	0.09528	5.829	0.001
S/P * END.Time	0.01043	2.907	0.03588	0.220	0.877
R/U * S/P	0.04796	9.242	0.005189	0.332	0.966
R/U * S/P* END.Time	0.06922	9.242	0.00749	0.479	0.892
Residual	15.205	725	0.0209		
Total	15.99	774			

Table 4: SNK test scores for wrist deviation (Radial/Ulnar) on transformed data

Wrist deviation	Groups significantly different at $p<0.05$		
	1	2	3
Neutral	0.513		
Radial 35% ROM		0.569	
Ulnar 35% ROM		0.584	
Radial 55% ROM			0.622
Ulnar 55% ROM			0.630
Sig.(p-value) for the difference in levels of radial/ulnar deviation within respective group		p=0.336	p=0.617

Table 5: SNK test scores for forearm rotation (Supine/Prone) on transformed data.

Forearm Rotation	Groups significantly different at p<0.05		
	1	2	3
Neutral	0.521		
Prone 30% ROM		0.557	
Supine 30% ROM		0.588	
Prone 60% ROM		0.593	
Supine 60% ROM			0.659
Sig.(p-value) for the difference in levels of prone/supine rotation within respective group		p=0.067	

Table 6. Regression Equations for TDS vs. Wrist Deviation & Forearm Rotation.

Discomfort vs. Forearm rotation (FR in %ROM)		
Deviation (%ROM)	Equation	R^2
55 radial	$TDS = 3E\text{-}05\ FR^2 + 0.0002\ FR + 0.5612$	0.98
35 radial	$TDS = 3E\text{-}05\ FR^2 + 0.0007\ FR + 0.5183$	0.9694
Neutral	$TDS = 1E\text{-}05\ FR^2 + 0.0004\ FR + 0.4882$	0.8224
35 ulnar	$TDS = 2E\text{-}05\ FR^2 + 0.0006\ FR + 0.5546$	0.9684
55 ulnar	$TDS = 3E\text{-}05\ FR^2 + 0.0006\ FR + 0.5791$	0.8516
Discomfort vs. Wrist deviation (WD in % ROM)		
Rotation (%ROM)	Equation	R^2
60 prone	$TDS = 5E\text{-}05\ WD^2 - 0.0002\ WD + 0.5109$	0.99
30 prone	$TDS = 3E\text{-}05\ WD^2 + 0.0004\ WD + 0.5077$	0.99
Neutral	$TDS = 3E\text{-}05\ WD^2 + 1E\text{-}04\ WD + 0.4823$	0.7317
30 supine	$TDS = 3E\text{-}05\ WD^2 + 0.0002\ WD + 0.5355$	0.95
60 supine	$TDS = 4E\text{-}05\ WD^2 + 8E\text{-}05\ WD + 0.5872$	0.878

Table 7. The results of the Univariate ANOVA where the electrical activity of FCR, FCU, ECRB & ECU for 10N flexion force were used as dependent variables separately.

		Electrical activity of FCR muscle			Electrical activity of FCU muscle			Electrical activity of ECRB muscle			Electrical activity of ECU muscle		
Source	df	Mean Sq.	F	p	Mean Sq.	F	p	Mean Sq.	F	Sig.	Mean Sq.	F	p
R/U	4	2.12	31.08	0.001	0.746	8.757	0.001	3.311	3.311	0.014	6.395	7.143	0.001
S/P	4	0.242	2.58	0.040	0.735	4.892	0.010	0.092	0.102	0.982	3.074	3.454	0.010
Participant	24	4.233	40.04	0.001	1.333	11.42	0.001	18.69	14.54	0.001	13.06	14.04	0.001
R/U * S/P	16	0.045	0.86	0.61	0.114	1.022	0.43	0.475	0.7	0.795	1.292	1.554	0.080
R/U * Participant	96	0.061	1.40	0.01	0.075	0.723	0.97	1.044	1.503	0.004	0.866	1.087	0.29
S/P * Participant	96	0.088	2.05	0.001	0.145	1.41	0.01	0.936	1.348	0.027	0.86	1.08	0.30
R/U * S/P * Participant	384	0.043	0.27	1.00	0.103	0.492	1.00	0.695	1.417	0.007	0.796	0.643	1.00

Table 8. SNK test scores for Wrist deviation (Radial/Ulnar) and Forearm rotation on normalised %EMG of FCR, FCU, ECRB and ECU muscles for 10N flexion force.

SNK test scores for different levels of wrist deviation on normalized %EMG

	FCR muscle		FCU muscle			ECRB muscle		ECU muscle	
Wrist deviation	Groups significantly different at $p<0.05$		Groups significantly different at $p<0.05$			Groups significantly different at $p<0.05$		Groups significantly different at $p<0.05$	
	1	2	1	2	3	1	2	1	2
Ulnar 55% ROM	0.86		0.93			0.61		0.65	
Ulnar 35% ROM	0.88		0.94			0.61		0.66	
Neutral		1.02	1.00	1.00		0.67	0.67	0.66	
Radial 35% ROM		1.08		1.05	1.05	0.68	0.68	0.74	0.74
Radial 55% ROM		1.12			1.11		0.73		0.80

SNK test scores for different levels of Forearm rotation on normalized %EMG

	FCR muscle	FCU muscle		ECRB muscle	ECU muscle	
Forearm rotation	Groups significantly different at $p<0.05$	Groups significantly different at $p<0.05$		Groups significantly different at $p<0.05$	Groups significantly different at $p<0.05$	
Neutral	0.94	0.94		0.63	0.65	
Prone 30% ROM	0.96	0.95		0.65	0.66	0.66
Supine 30% ROM	1.00	0.98		0.66	0.70	0.70
Prone 60% ROM	1.01	1.05	1.05	0.67		0.75
Supine 60% ROM	1.04		1.12	0.69		0.76

Table 9. Comparison of some SDS values from this study with some data from Carey & Gallwey (2005)

Mean values of SDS							
Present study						Carey & Gallwey (2005)	
wrist deviation (%ROM)	Forearm rotation (%ROM)					wrist deviation (%ROM)	without forearm rotation
	-60	-30	0	30	60		
-55	6.61	4.2	4.07	4.91	7.36	-55	4.07
-35	4.39	3.23	2.76	4.38	6.45	-38	2.32
0	2.83	2.62	1.8	3.21	4.15	0	1.06
35	4.2	3.87	3.41	4.6	5.94	38	1.83
55	5.68	5.11	3.71	5.61	7.67	55	1.65